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THE USE OF GPS FOR EVALUATING INERTIAL MEASUREMENT UNIT ERRORS

by

Sun Mei

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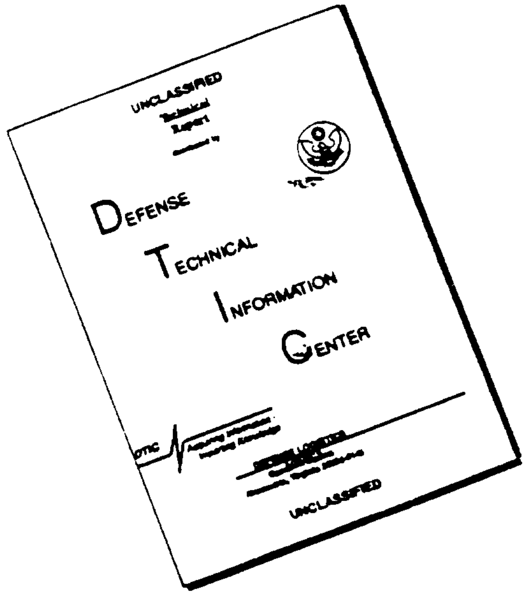

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The Use of GPS for Evaluating Inertial Measurement Unit Errors

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ABSTRACT During missile flight tests, a trajectory reference system based on GPS can be used in place of conventional radars. Due to the high precision of GPS trajectory references, it is, therefore, possible to make use of them in order to evaluate missile inertial measurement unit performance. Before two recent launches of Hepingbaoweizhe (peacekeeper) missiles, GPS transmiters and three wave band antennas were installed on them. On the basis of GPS measurement ranges and range increment data, use was made of kalman wave filter methods to estimate individual IMU errors. Results clearly demonstrated that GPS is superior to radar.

SUBJECT TERMS Global positioning system Inertial measurement unit Error Kalman filtering

1 BACKGROUND

GPS is the satellite navigation system which the U.S. government decided to develop in the early 1970's. From the launching of the first two GPS satellites in June 1989, to 9 March 1994, deployment was completed.

The system in question deploys 24 satellites at an altitude of 20000km. They are dispersed in 6 orbital planes. Each orbital plane has 4 satellites. Among these, 21 satellites are normally utilized. 3 satellites are spares. Operating orbits are metasynchronous (operating periods are 11h58min). GPS is capable of all weather operations. Accurate three dimensional positions, three dimensional velocities, and time data are /70 supplied for any moving object from the ground to an altitude of 9000km. Maximum positioning precisions are capable of reaching inside 10m. Velocity measurements are capable of reaching 0.1-0.01m/s. Time transmission precisions are 10-6 s. Due to the world wide usability of GPS, the range of GPS applications gets broader and broader. Trajectory references associated with missile flight tests are only one example of GPS application. This is particularly the case with utilizing GPS to calculate missile IMU errors. As far as key components of deep space rockets, carrier rockets, and other large model rockets are concerned, IMU generally include three accelerometers, three gyroscopes, and related hardware and electronic equipment. IMU use accelerations needed to produce speed and position information and attitude data to supply navigational computers. Speed and position data go through guidance and control computers in sequence, making carrier devices follow ideal trajectories in flight.

For the last few years, the U.S. Navy--during ballistic missile flight tests launched from Trident submarines--has already made use of measurement systems based on GPS to evaluate IMU errors. The Navy experience clearly demonstrates that trajectory reference values supplied by GPS are better than those supplied by radar, achieving relatively higher credibility in calculations of IMU errors. In order to demonstrate the effectiveness of using GPS in evaluating U.S. Air Force ICBM type missile IMU errors, two firings of active service Hepingbaoweizhe (peacekeeper) missiles were fitted with GPS transmiters and three wave band antennas before launch from Califorina's Vandenburg Air Force Base toward the Kwajalein atoll target area in the Pacific.

As far as this technology is concerned, with regard to successful applications associated with Air Force projects, it is necessary to reconcile several key areas of difference between the Navy Trident missiles and the ICBMs the Air Force currently has. The improtant differences include missile "basing" modalities (differences between types operating at sea and fired from fixed land based silos), ranges, accuracies and structures, and, in particular, missile antenna design. Besides this, the Navy makes use of GPS L1 and L3 wave bands to gather data. Due to characteristics of L3 wave band, during ICBM type missile flight tests, the Air Force did not make use of L3 wave bands. However, during Hepingbaoweizhe (peacekeeper) missile flight tests, they opted for the use of L1 and L2 wave bands.

2 GPS HARDWARE SET UP

Two firings of Hepingbaoweizhe (peacekeeper) missiles were used in order to empirically verify GPS effects on IMU calculations. Their nomenclatures were GT-06 and GT-07. They carried dual frequency GPS transmiters and three wave band antennas. GPS receivers produced trajectory data from GPS signals recieved. However, transmiters, by contrast, merely used different carrier frequencies to transmit GPS data. Due to the cheap price, light weight, and low electrical power consumption associated with transmiters, and it being possible to still carry out calibration of GPS signals transmited against GPS data after flights, it was, therefore, better to opt for the use of transmiters and not use receivers. Three wave band antennas allow the reception of L wave band GPS signals and, in conjunction with that, the use of S wave band to transmit SPS signals. S wave bands are also used in missile telemetry systems. Besides this, missiles also carried a C wave band response device used in order to assist radar tracking.

Hepingbaoweizhe (peacekeeper) missile GPS tests make use of L1 (1575MHz) frequency CA code and utilize L2 (1227MHz) frequency P code. In order to reduce electric power consumption of transmiters, during transmission, 20MHz L2 P code signals are taken and compressed into a 2MHz band width. Of course, this will cause some losses in resolution. L1 signals are used in order to directly produce ranges and missile tracking data associated with distance increments which are derived from phases. However, L2 signals, by contrast, are used in order to correct for atmospheric refraction. For the sake of this objective, the feasibility of taking L2 signals and compressing them had never been empirically tested before. If there was no valid L2 data, it was only possible to make use of relatively crude corrections based on experimental models in order to calibrate for atmospheric refraction.

As far as each flight iteration was concerned, from 6 satellites, it was possible to obtain usable data for the entire propulsion flight stage. Transmited GPS signals were recorded by two Pillar Point ground receiving stations located in the vicinities of Vandenberg Air Force Base and San Francisco. When there were signal attenuations with one or the other ground station (for example, separation between rocket stages), having two ground receiving stations, it was possible to provide data redundancy and continuity.

3 IMU EVALUATION MEHTODS

The objectives of IMU evaluations are to determine overall errors associated with target misses given rise to because of IMU; to specify--among the main IMU error types (for example, accelerometers, gyroscopes, IMU clocks, and initial conditions)--the influences of each type; and, to determine as much as /71 possible--among the various types of things having an influence--the individual natures of the largest ones (for example, bias and scale factors associated with each instrument). IMU telemetry data and ranging equipment (GPS or radar) survey data obtained in missile flight tests is already known. Use is made of kalman wave filter methods to carry out calculations with regard to IMU calibration errors, instrument drift errors, and initial conditions (including alignment) errors, thereby making it possible to calculate estimated values for the influences of various error items as well as entire IMU errors on target misses.

With regard to ordinary methods associated with IMU error evaluations, they process a measurement value produced by measurement data from IMU telemetry data and ranging equipment. The measurement value in question is a function of IMU errors and ranging equipment measurement errors. Combining with each other differential equations associated with error transmission in inertial guidance systems and error models associated with accelerometers, gyroscopes, IMU clocks and initial conditions, one obtains IMU error sensitivities with regard to these measurement values. In the same way, making use of ranging equipment error models, one obtains sensitivities with regard to GPS or radar error measurement values. In regard to the sensitivities associated with the measurement values and errors in question, kalman wave filtering is carried out, solving for estimated values associated with flight errors. It is thereby possible to calculate the influences of IMU error values in landing errors. The flow chart, as shown in Fig.1, for the use of GPS with regard to classical IMU evaluation, is similar to the flow chart associated with using radar data for evaluation.

4 MEASUREMENTS

The first step in calculating IMU hardware errors is to set up an ideal navigation trajectory. This type of trajectory is obtained on a high precision computer using optimum estimate values for initial conditions as well as WGS-84 8x8 gravity values supplied by the Department of Defense (including gravity values associated with launch areas) and original accelerometer data obtained processing telemetry using precision navigation equations. Any errors in the trajectory in question, by definition, are given rise to by IMU errors. As a result, this trajectory is designated as being IMU-indication trajectory.

Once IMU-indication trajectories are set up, they are converted to range measurement domains (for GPS they are range and range increments, for radar they are range and range rate of change). In conjunction with this, they are synchronous with distance measurement values and errors gotten. These error values will not be equal to zero. The reason is that IMU errors, ranging errors associated with the creation of models and without the creation of models, as well as random noise exist.

With regard to GPS and measurement system data--speaking in terms of ranges--they express the length of the paths from satellites to missiles and then to ground receiving stations. Speaking in terms of range increments, they express the change increments associated with the lengths of the paths in question within a certain time interval. These data are compiled, and, in conjunction with that, corrections are carried out with regard to ionosphere, troposphere, and antenna arm effects, already known clock and timing errors, relativity, as well as other influences. The differences between these measurement values and corresponding IMU-indication amounts are called single path distance and distance increment (or Doppler) measurement values. In order to eliminate common missile to receiver down link line errors, single path measurements form pairs to carry out progression. The results are used in kalman wave filter measurements.

Wave filter device measurement values are still only functions of IMU and GPS errors as well as noise. Moreover, there is no relationship with relatively large GPS down link line errors.

5 ERROR MODELS

During IMU evaluations, IMU error models of which use is made can be different. However, generally speaking, error quantities included must give consideration to accelerometers, gyroscopes, IMU clocks, and initial conditions. One type, which has already been successfully used in IMU radar analysis techniques, is the selecting of 12-15 of the most significant items in a relatively large IMU model. Actual flight test data are utilized to carry out research verification. When making use of GPS data, it is necessary to have even more error terms. This is due to GPS measurement quality being higher than measurements obtained using radar. As a result, a total of 73 terms are made use of--including 33 accelerometer terms, 30 gyroscope terms, 1 clock term, as well as 9 initial condition terms. When IMU error models begin to be set up, use is made of random quantities, and, in the entire flight, they are treated as constants. Of /72
course, speaking in terms of the influences of errors on navigational configurations, GPS or radar measurements, they are, in all cases, functions of time.

$$X_{IMU}(t_{k+1}) = X_{IMU}(t_k)$$
$$M^i_{R/IMU}(t_k) = \partial R^i(t_k) / \partial X_{IMU}$$

In the equations: XIMU is the IMU error source vector;

$M^{i}_{R/IMU}$ is the IMU error source sensitivity associated with satellite to missile distances.

Speaking in terms of each satellite, typical GPS error models include 12 terms--5 terms are globally related, as well as random measurement noise. These errors include satellite position, speed, clock errors, troposphere scale factor errors, antenna Doppler errors, distance and distance increment system errors, arm errors, as well as relative time determination errors. When setting up models, a certain number of errors are taken to be random constants (or bias values):

XGPS/BIAS (tK+1) = XGPS/BIAS(tk)

Other model error terms are related random variables associated with variations in accordance with the laws of exponents (Gauss-Markov process):

XGPS/MRKV (tk+1) = exp(-β(tk+1 - tk))XGPS/MRKV (tk)+W(tk)

Besides this, E[W(tk)2] = σ2* {1-exp(2β(tk+1 -tk)}

With regard to bias values and Markov errors, their influences on GPS measurements are functions of time in all cases:

$$M^{i}_{R/GPS}(t_k) = \partial R^{i}(t_k) / \partial X_{GPS}$$

$$M^{i}_{D/GPS}(t_k) = \partial D^{i}(t_k) / \partial X_{GPS}$$

In equations: $M^{i}_{R/GPS}$ is the sensitivity associated with GPS error sources for distances from satellites to missiles;

$M^{i}_{D/GPS}$ is the sensitivity associated with GPS error sources for distances derived from satellite to missile phases;

XGPS is GPS error source vector.

Distance measurement noise V^{i}_{R} makes use of Gauss white noise to build models. In distance increment measurements, V^{i}_{D}

and V'_{AC} both make use of Gauss white noise to construct models, although actual past distance increment measurement values with respect to V'_{AC} were noncorrelative.

V'_R is GPS distance measurement noise. V'_D is measurement noise associated with distance increments derived from GPS phases. V'_{AC} is single step anticorrelation measurement noise.

Classical radar error models have already been utilized for a good number of years in ICBM tests. They include distance bias value errors, distance speed bias value errors, radar position measurement errors, relative time determination errors, and random measurement noise terms. When constructing models, errors are normally taken to be random constants, although distance value bias errors are capable of being viewed as a random moving process. During analysis, because angular data includes relatively large amounts of noise, it is normally useless.

6 MEASUREMENT MATRICES

Use is made of IMU-indication trajectories and IMU error source models to calculate the sensitivity of navigational configurations with regard to unit IMU errors. If GPS is used in distance measurements, IMU error sensitivites in regard to each satellite line are converted into distance and distance increment coordinates, obtaining range and range increment measurement sensitivites. Choosing any two GPS sensitivites from among all measurement lines--with regard to their solution error values--they are taken as consistent with GPS kalman filtering. As far as kalman wave filter device measurement values are concerned, calculations are also carried out with respect to unit GPS error source sensitivities. The same type of procedure is used with radar. /73

7 KALMAN WAVE FILTER DEVICES

Before filtering measurement data, one first produces measurement noise covariances, transfer matrix elements, process noise covariance elements, and initial error state covariance matrices.

In wave filter devices, measurement values and unit error sensitivities are compared in order to form IMU estimate values and estimate values for amounts of error associated with distance measurements. Kalman state vectors are composed of a series of scalar error sources derived from IMU, GPS, or radar models. As was described before, measurement vectors are composed of difference values between IMU and GPS (or radar) indication trajectories. Measurement transformation matrices--or, to say it simply--measurement matrices are composed of partial derivatives associated with measurement coordinates transmited from error model equations to speeds and positions in space and, in conjunction with that, transformed to GPS or radar. Measurement matrices are a time function. Once wave filtering devices have obtained estimate values for IMU error amounts, use is then made of rip cord point error sensitivities and previously calculated target miss deviation parameters, broadcasting estimate values to impact spaces.

Because errors in one satellite or radar do not influence the measurements associated with other satellites, measurement matrices include large numbers of zero elements. During the actualization of equations, this type of characteristic proves useful in reducing the number of iterations of calculations.

Speaking in terms of a different aspect, actual situations are complicated. The reason is that data obtained from different GPS satellites is not uniformly usable. In the same way, at different instants during the entire flight period, radars will usually acquire, lose, and reacquire in tracking. Because the number of satellites or radars acquiring valid observation data is changing, as a result, the total number of measurement iterations changes from time to time. The handling for this type of situation is to go through adjustments of the size and composition of measurement vectors, covariances, and measurement matrices in order to facilitate only including those measurement results which correspond to valid satellites or radars.

8 FLIGHT TEST RESULTS

"Peace" GPS hardware was designed in accordance with the requirements of GT-06 and GT-07 flight tests. L1 CA code is used in order to obtain measurement data and measurement increment data derived from phases. L2 compressed P code signals are also used to provide calibration for atmospheric refraction after they are restored.

In GT-06 and GT-07, both GPS and radar data are used in succession. Considering that the reliability of estimate values is not the same, there are problems presented with regard to the relative effectiveness of the two types of measurement systems.

The capability of wave filter devices to evaluate IMU error amounts is partially dependent on geometrical relationships associated with firing range measurement systems. The general measurement for this type of geometrical relationship is PDOP (precision dilution of positions). In order to guarantee the obtaining of good data for evaluating IMU and to act as planning standards before flights, there is a requirement that GPS PDOP be 35 or smaller. During entire flights, 6 GPS satellites are then capable of supplying extremely good geometrical relationships. On the other hand--speaking with regard to most flight orbits--geometrical relationships indicated by radar PDOP are very bad. These flight tests make use of typical radar arrays. Along the California coast, use is made of 6 to 8 radar stations. In Hawaii, use is made of one or two more. Before missiles appear above the California base horizon, radar PDOP become infinitely large. After that, when missiles fly toward space, PDOP clearly drop down. Middle range (Hawaii) radar soundings improve and are clear.

Another index of wave filter device performance is indeterminateness in after checks or estimated values. Table 1 shows indeterminate estimate values associated with GT-07 GPS and radar unitized fall point deviations. These are idealized indeterminacies. In terms of indeterminateness in engineering, they must be somewhat larger. The reason is that a priori indeterminacies, in and of themselves, are nothing else than estimated values. Moreover, error models are merely approximate descriptions of real objects. Even though this is the case, indeterminacies associated with estimated values still supply a relative scale to compare GPS and radar. With regard to estimated values associated with complete point of fall deviations given rise to by IMU, GPS possesses relatively low (relatively good) indeterminateness. Moreover, with respect to estimated values for point of fall deviations given rise to by primary IMU error sources, is is also GPS which has relatively low indeterminacy.

Attention should be paid to the fact that, due to high correlation of estimated values between various sets of errors, the indeterminacies of the two systems with regard to estimated values for entire fall point deviations must, therefore, all be lower than estimated values given rise to by this set of errors.

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To say it another way, the correlation of estimated value errors for one state and estimated value errors for another state are extremely high.

One measure related to the capacity of wave filter devices to estimate IMU errors is the restoration ratio associated with errors. Error restoration ratios are ratios between the square root of final error covariance matrix corresponding diagonal elements and the square root of the same diagonal elements of the initial covariance matrix. Restoration ratios being low indicates that estimated values are relatively good. Measures with regard to classifying estimated error value indeterminacies are similar. They are ratios of circular probability errors derived from final indeterminate matrices divided by circular probability errors derived from initial indeterminate matrices.

Table 1 Estimated Value Indeterminacies Corresponding to GT-07 and GPS

	GPS		(3) 雷达	
	(1) 航向	(2) 横向	(1) 航向	(2) 横向
(4) 初始条件	0.15	0.15	0.19	0.29
(5) 加速度表	0.22	0.08	0.23	0.08
(6) 陀螺	0.02	0.13	0.03	0.30
(7) 时钟	0.13	0.002	0.17	0.002
(8) 整个	0.06	0.006	0.15	0.18

Key: (1) Course Direction (2) Transverse Direction (3) Radar (4) Initial Conditions (5) Accelerometer (6) Gyroscope (7) Clock (8) Entirety

Fig.2 shows error restoration ratios for GPS and radar classifications used in GT-07 as well as the entirety. It again demonstrates that GPS, when estimating IMU classification errors and entire IMU errors, is better than radar. In both cases of GPS and radar, estimates of entire errors were better than classification errors. Fig.3 shows distributions associated with various individual error restoration ratios. With regard to 0.9 or smaller restoration ratios, GPS is capable of estimating 25 terms. Radar is only capable of estimating 9 terms. In this way, in large scale IMU models, when the ability of the two systems to discriminate with regard to the influences of various quantities is limited, the capabilities of GPS clearly exceed those of radar.

Using GPS to evaluate IMU produces an unexpected result. That is nothing else than the precise determination of launching site measurement errors. This type of error cannot be clearly shown in results associated with measurements using radar.

9 CONCLUSIONS

"Peace" GPS flight tests were very successful. All flight objectives related to GPS were attained. The performance of all flight hardware, post flight tracking hardware and software, as well as post flight IMU evaluation software met design specifications in every case. Post flight evaluations of GPS data pointed out that GPS will supply an appropriate trajectory reference value for purposes of firing range safety. In order to evaluate IMU performance, data was obtained. Compressed L2 signals were successfully used in calibration for atmospheric refraction. Making use of GPS and radar, estimates for whole point of fall deviations given rise to because of IMU hardware errors were obtained. Various types of scales associated with the observability of kalman wave filter device perfomance and errors--for example, indeterminacy of overall estimated values for PDOP as well as overall error restoration ratios--clearly show that GPS, in the area of estimating entire point of fall deviations given rise to because of IMU errors, has comparatively higher reliabilties than radar. Making use of GPS and radar, various types of measurements have been obtained of observable wave filter estimate device performance and errors with regard to point of fall deviations given rise to because of principal IMU errors. For example, indeterminacies associated with PDOP and primary error estimated values as well as classified error restoration ratios, clearly show that, GPS, in the area of point of fall deviations given rise to because of IMU primary errors, is better than radar estimates. However, the reliabilities of GPS and radar, with regard to estimates of primary fall errors, are both lower than reliabilities associated with estimates of overall point of fall deviations given rise to because of IMU errors.

Making use of GPS and radar, various types of observable measurements were obtained for estimated value wave filter device performance and errors. For example, PDOP as well as single error restoration ratios clearly show that GPS, in the area of estimating point of fall deviations given rise to because of various individual IMU errors, is better than radar estimates. In particular, the error terms which GPS is able to see are /75 clearly more numerous than radar. However, the reliabilities of GPS and radar are both low with regard to the majority of single error estimates. As a result, overall point of fall deviations given rise to because of IMU are very clear. Point of fall deviation estimates associated with various individual errors are highly correlated. However, point of fall deviations given rise to because of any single error source term are still not very clear.

It has been verified that, during flight tests, GPS is one valuable tool to evaluate IMU errors. It is able to provide extremely good geometrical relationships and low noise data. As far as use in providing IMU error estimates is concerned, it is much better than those obtained in the past using radar.

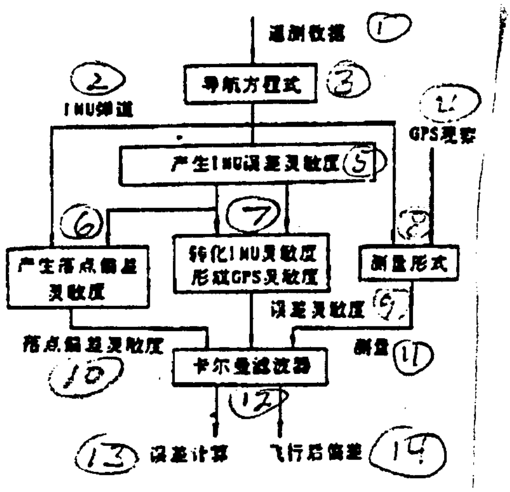

Fig.1 Post Flight IMU Evaluation

Key: (1) Observation Data (unclear) (2) IMU Trajectory (3) Navigational Direction (unclear) Form (4) GPS On Site Observations (unclear) (5) Produce IMU Error Sensitivities (6) Produce Point of Fall Deviation Sensitivities (7) Convert IMU Sensitivities to Form GPS Sensitivities (8) Measurement Forms (9) Error Sensitivities (10) Point of Fall Deviation Sensitivities (11) Measurements (12) Kalman Wave Filter Devices (13) Error Calculations (14) Post Flight Deviations

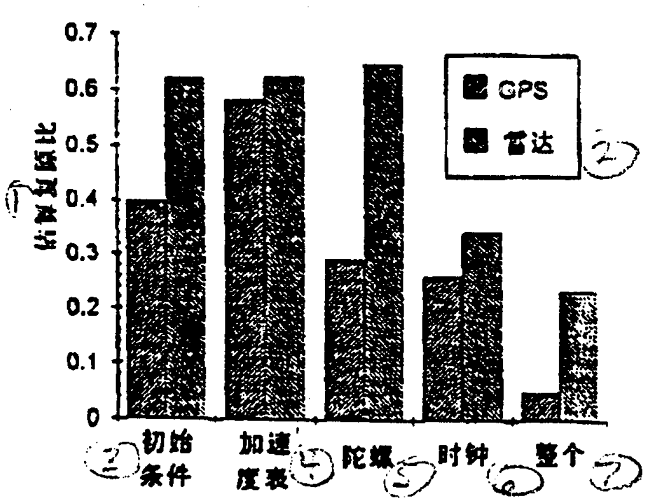

Fig.2 Key GPS and Radar Error Restoration Ratios

Key: (1) Estimate Restoration Ratio (2) Radar (3) Initial Conditions (4) Accelerometer (5) Gyroscope (6) Clock (7) Entirety

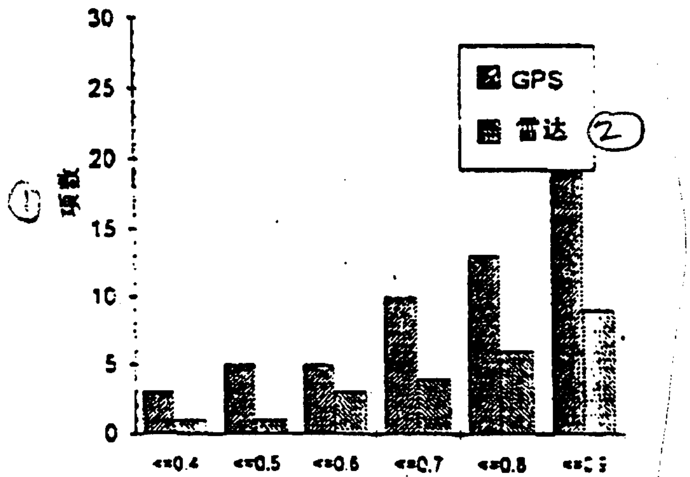

Fig.3 Individual GPS and Radar Error Restoration Ratios

Key: (1) Term Number (2) Radar

REFERENCES

1 John J. Dougherty. Hossny El-Sherief. David S. Hohman. The use of GPS for evaluating inertial measurement unit errors. AIAA-93-3887-CP: 1678-1684

2 导航星全球定位系统——世界未来的导航系统. 中国航天, 1993年1月

3 GPS的发展前景. 国外空间动态, 1993年5月

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